Design & Health Prognosis of Composite Structural Durability

John Bausano, Steven Phifer, Michael Hayes, Scott Case & Jack Lesko
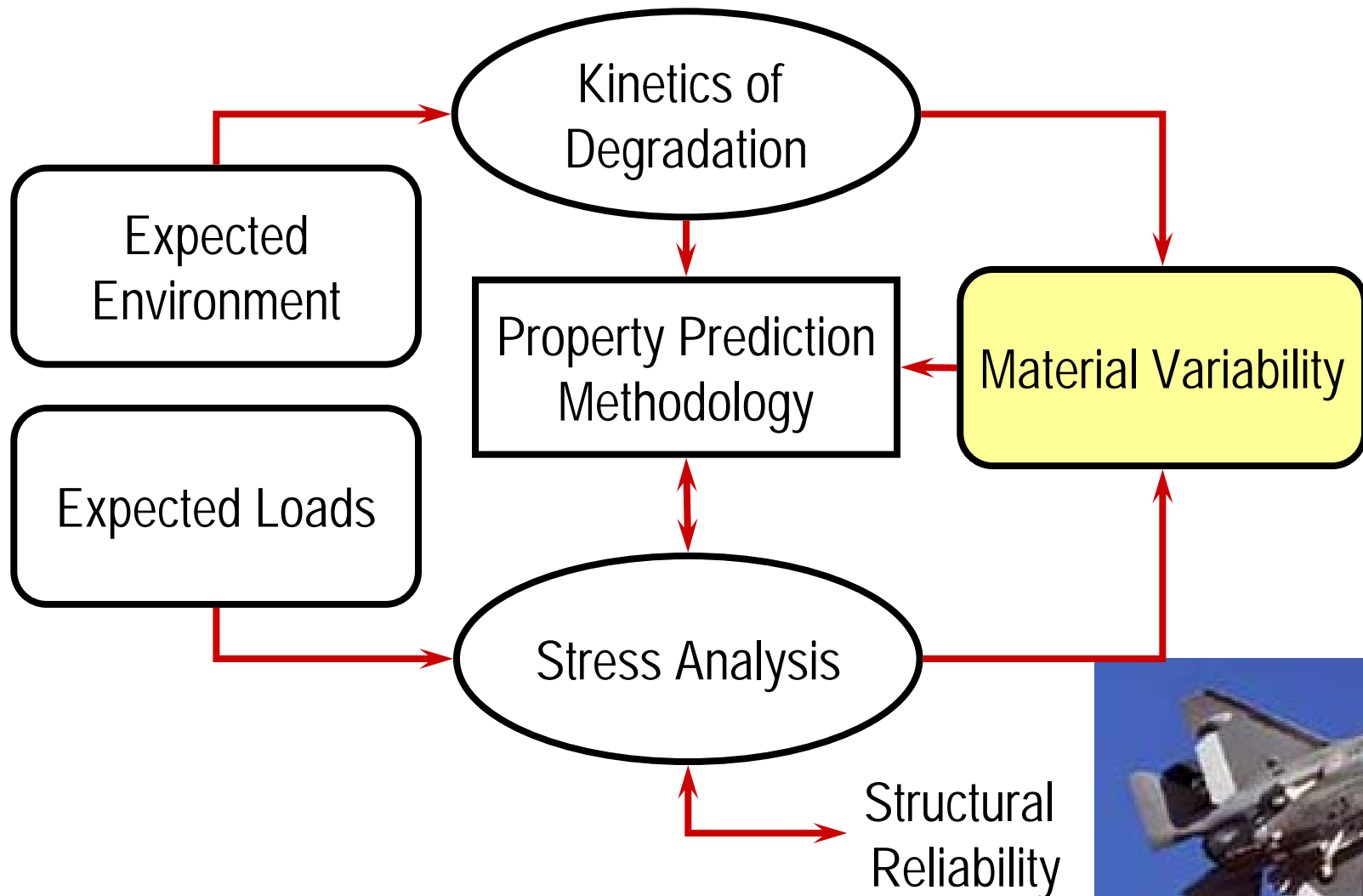*Materials Response Group*
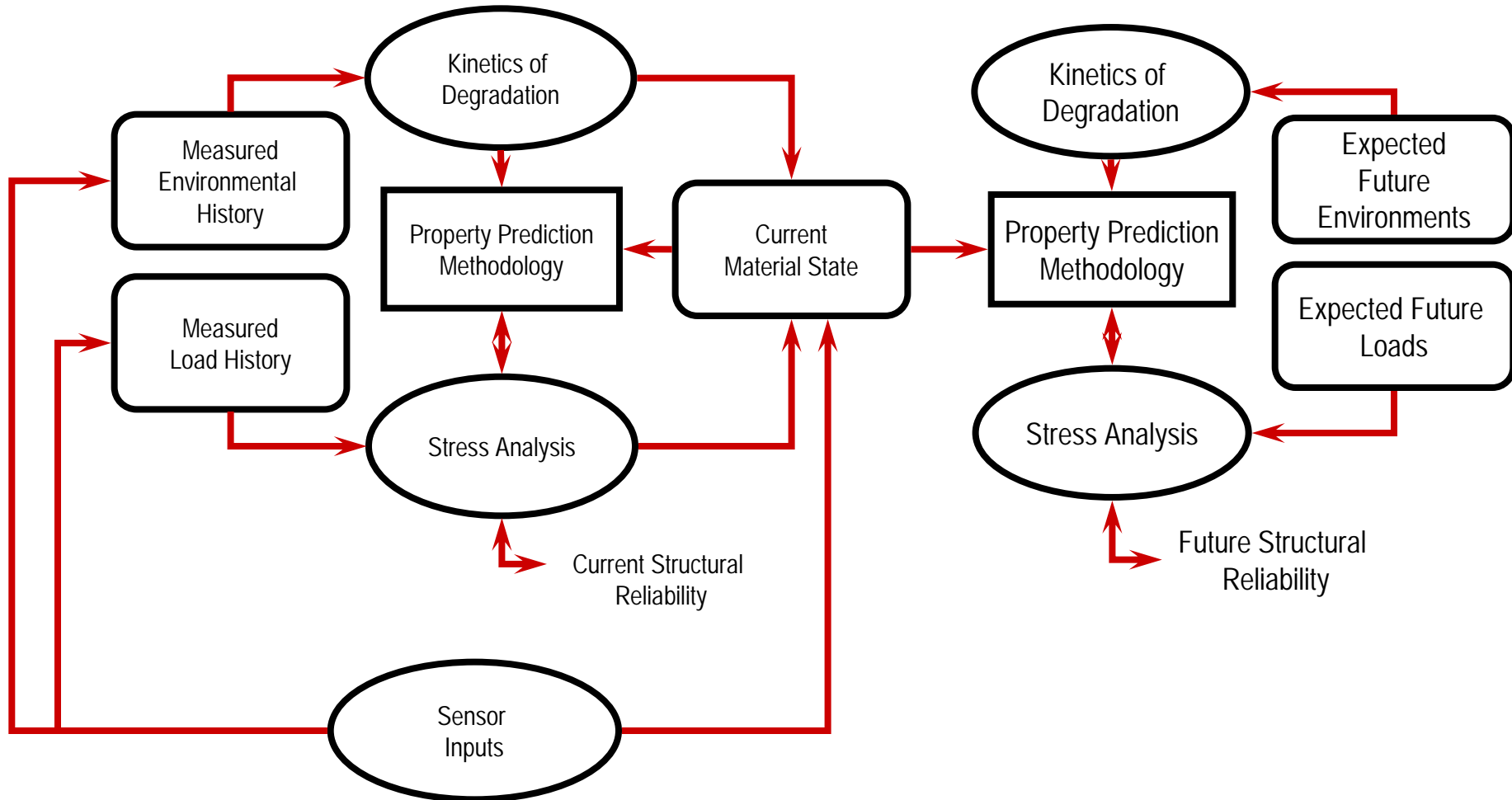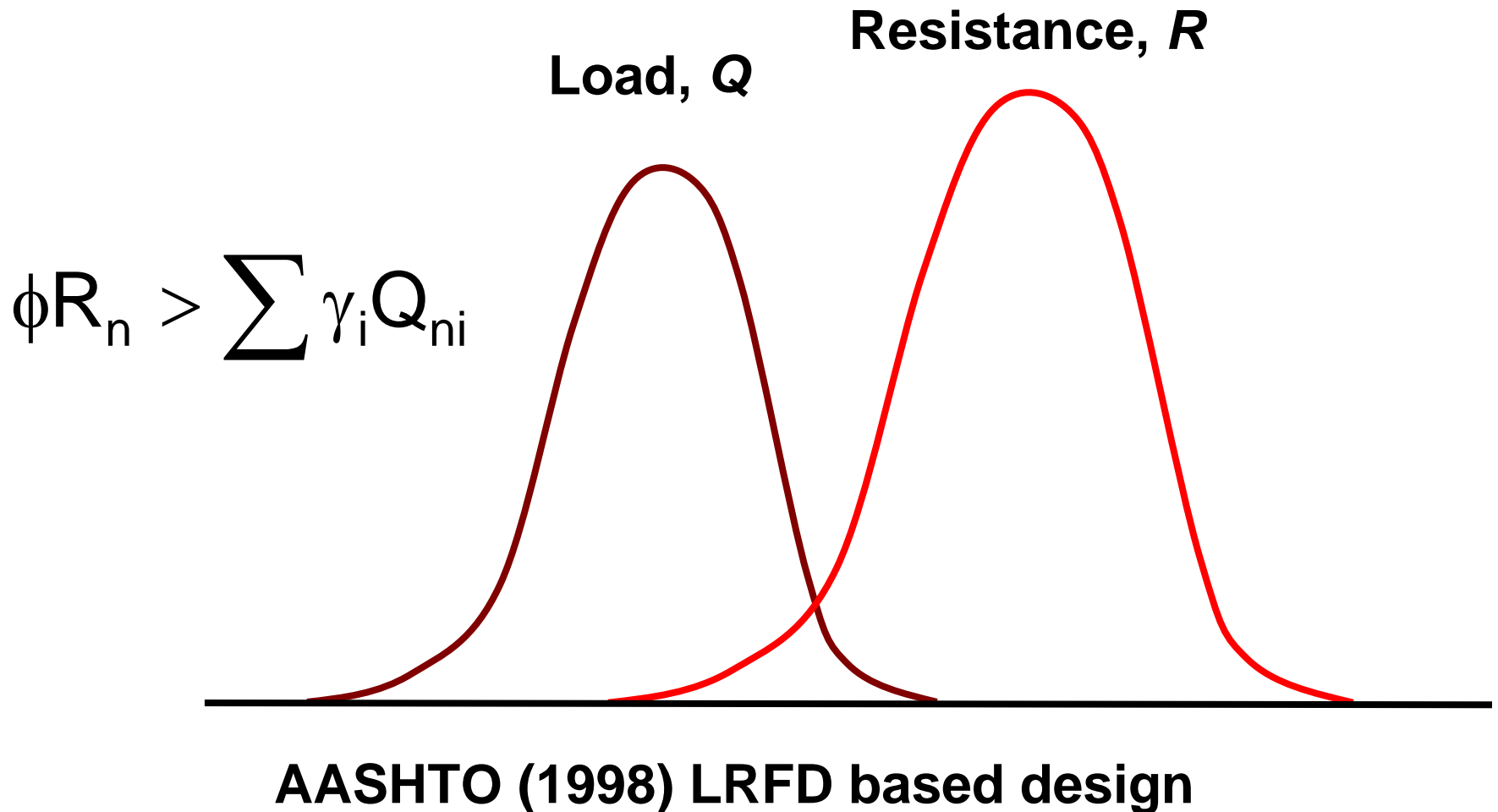*Department of Engineering Science & Mechanics*
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VirginiaTech
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Where are We Working Now?

Where Would We Like to Be?

Load & Resistance Factor Design (LRFD)

$$\phi R_n > \sum \gamma_i Q_{ni}$$

Load, *Q*

Resistance, *R*

AASHTO (1998) LRFD based design

Design Guide Approach

User supplies loads and level of acceptable risk based on _change_ in Resistance

Resistance, _R_

Cumulative Probability

B-Basis

A-Basis

Design Load/Stress

Level of Risk
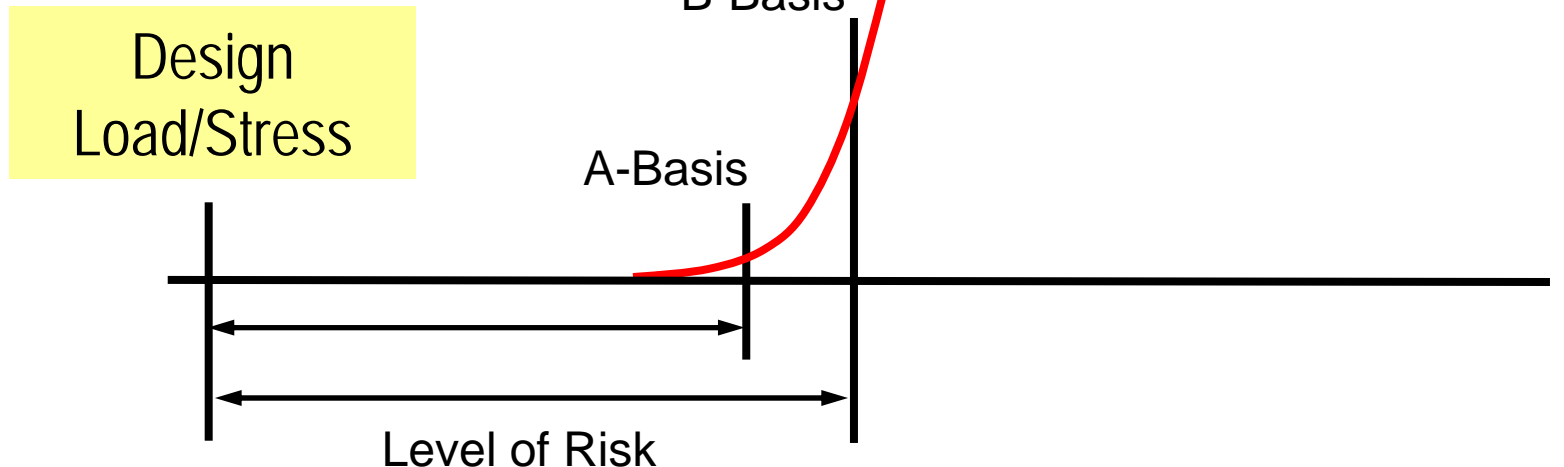
How Does the Resistance Change?

FRP Life prediction is required as a function of load and environmental history to assess the changes in Resistance
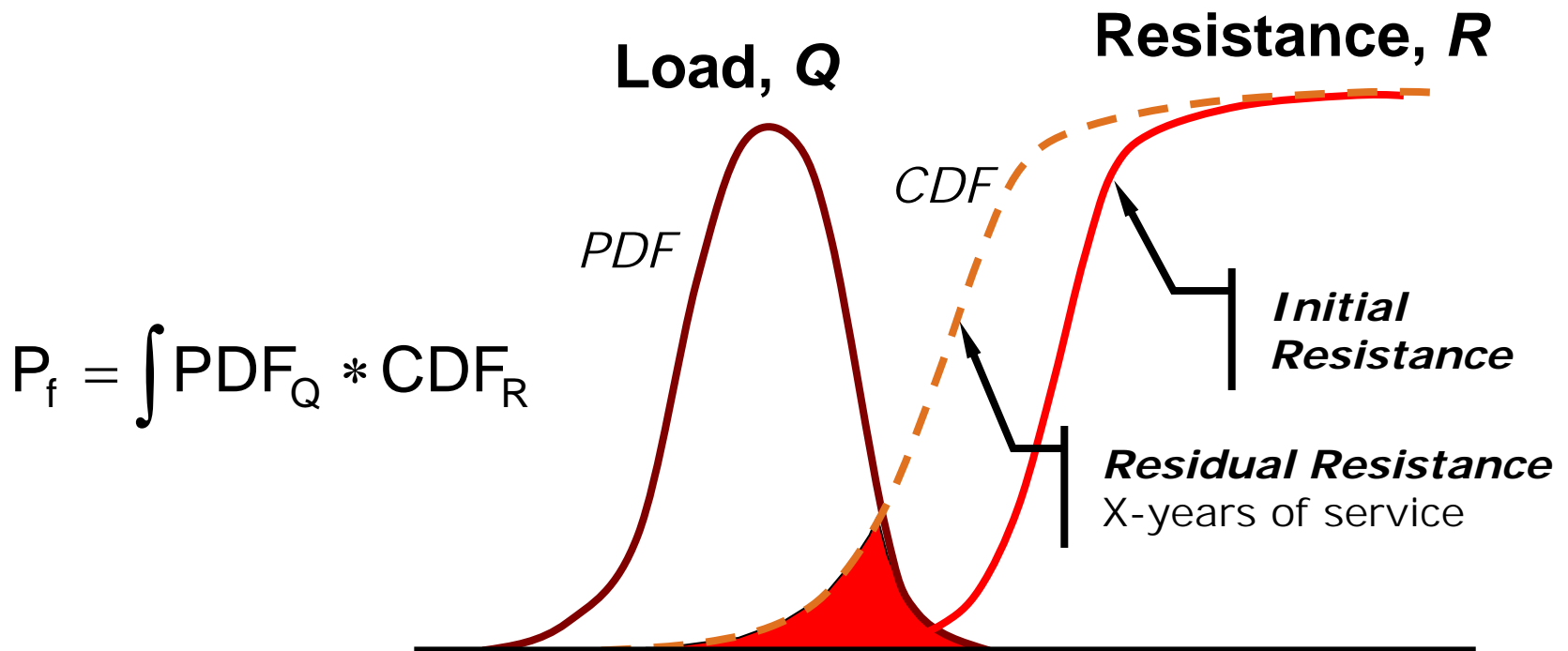
Resistance, R

A, *Residual Resistance*
X-years of service

B, *Residual Resistance*
X-years of service

Initial Resistance
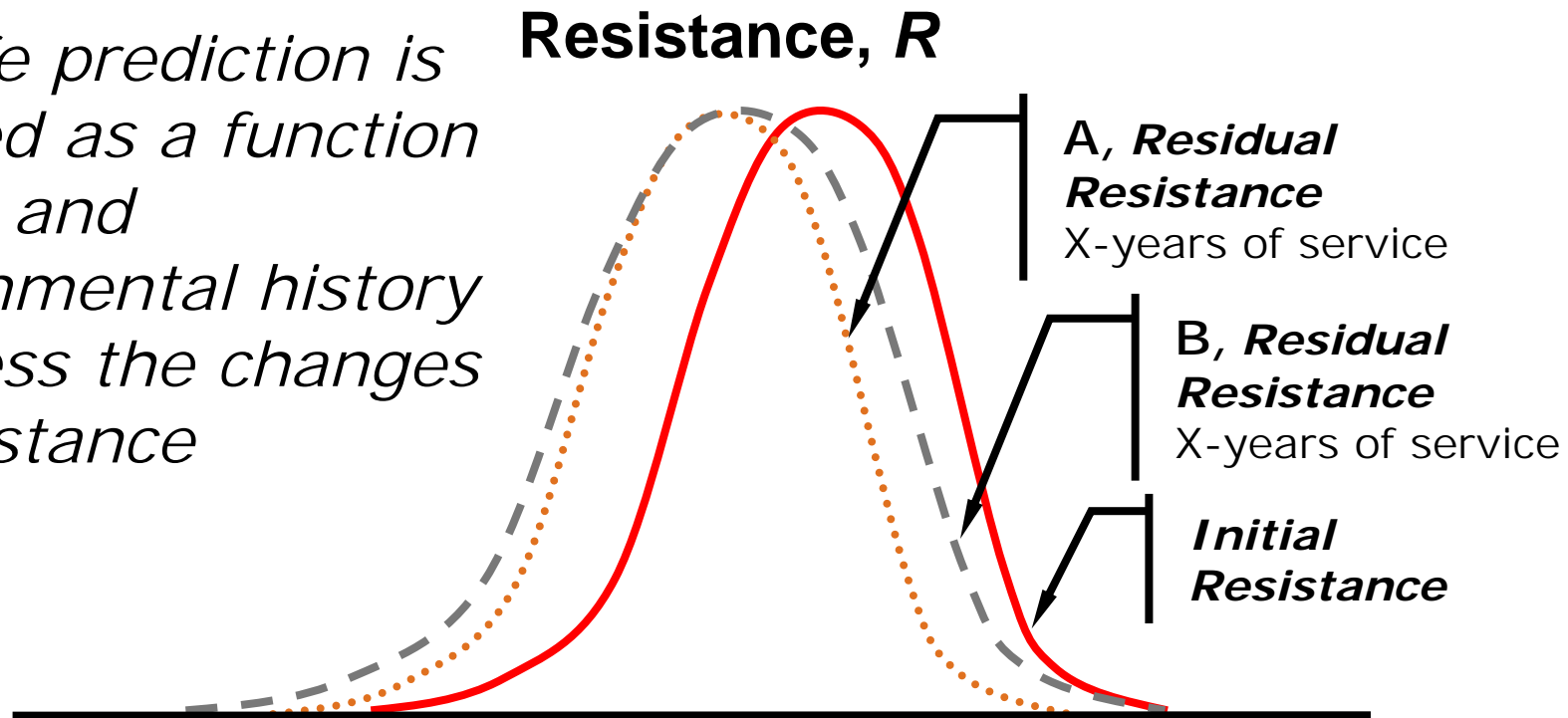
**"Emphasis on Combined Environments"
CERF/MDA Durability Gap Analysis**

Developing Guidance on ϕ

$$\phi = \left(\frac{\mu_R}{R_n}\right) \exp\left(-\alpha_R \beta V_R\right) \quad \text{where} \quad \beta = \frac{\mu_G}{\sigma_G} \quad \text{and} \quad G = R - Q$$
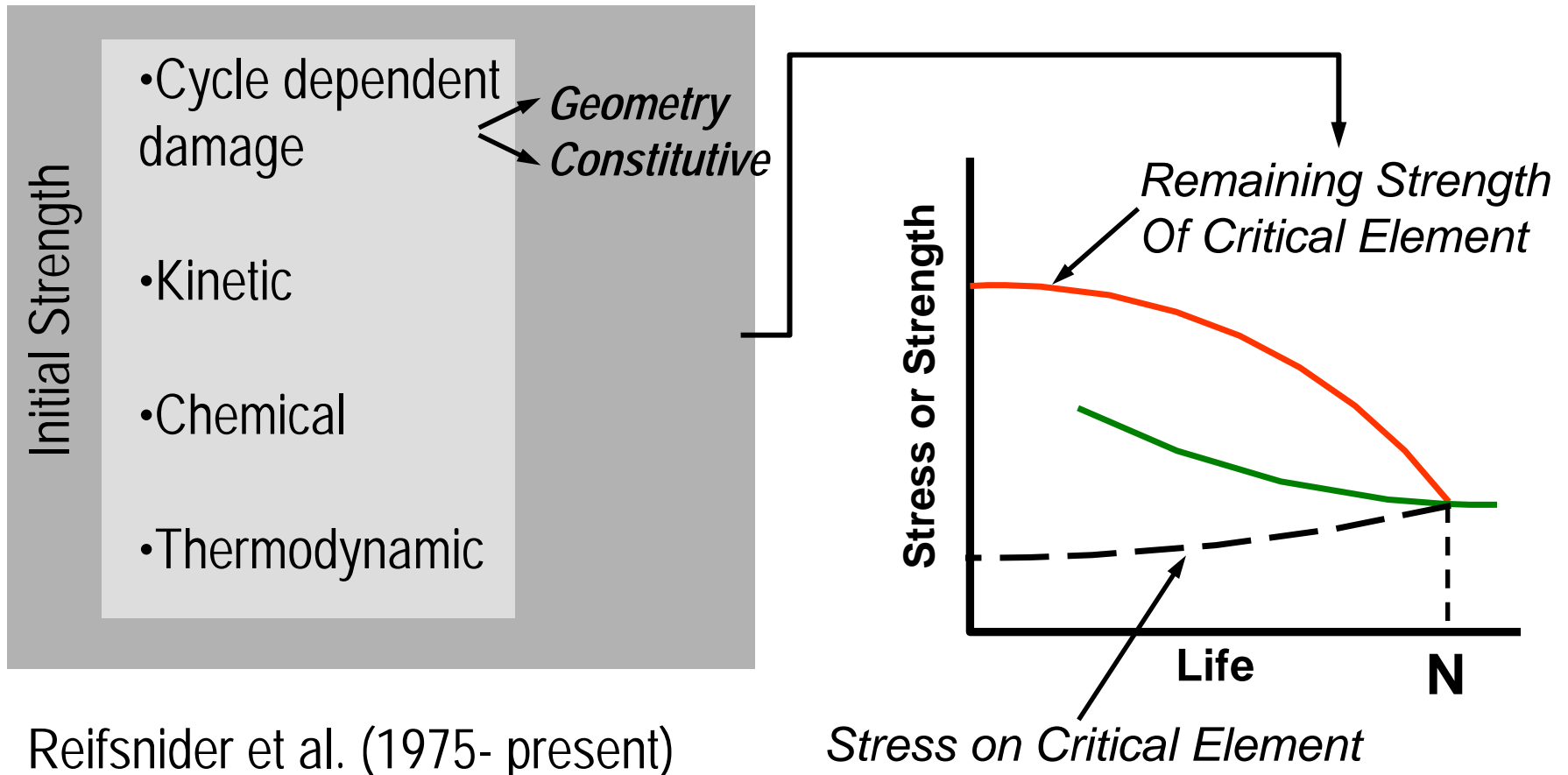
(FORM) – Hasofer & Lind (1974)

$$P_f = \int PDF_Q * CDF_R$$

Load, *Q*

Resistance, *R*

PDF

CDF

Initial Resistance

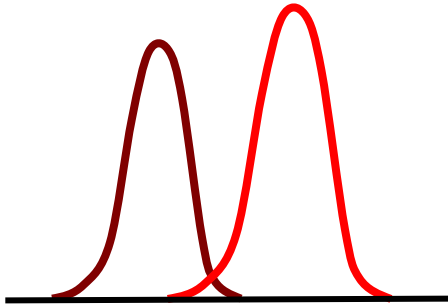***Residual Resistance***
X-years of service

Estimating Remaining Strength & Stiffness

FRP composites durability is best described by nonlinear cumulative damage approaches where residual strength and stiffness are tracked during life

Degradation Processes

- Cycle dependent damage → *Geometry* / *Constitutive*
- Kinetic
- Chemical
- Thermodynamic

Initial Strength

Stress or Strength

Remaining Strength Of Critical Element

Life

N

Stress on Critical Element

Reifsnider et al. (1975- present)

Simulation Approach

- **Develop estimate on resistance based on *stress analysis/material***
- **Develop *load/environment* history based on statistical description (Monte Carlo Simulation)**

No   **?**   Yes

- **Input material characteristics** (S-N curve, stiffness and strength reduction as a function of environment - *including statistical description*)

Life Prediction

Stress or Strength

Life
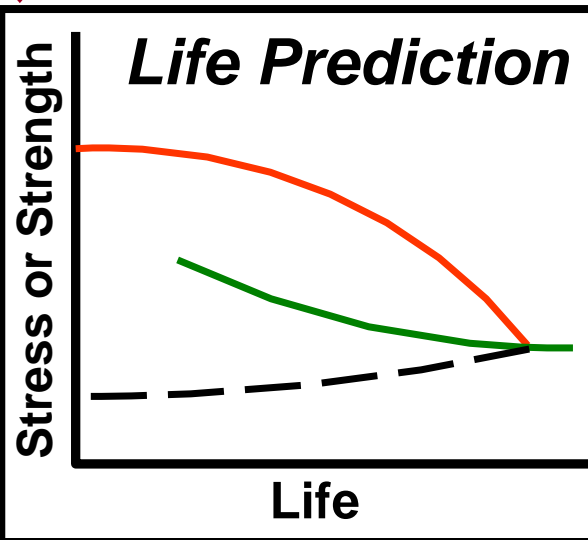
Compute ϕ & P_f
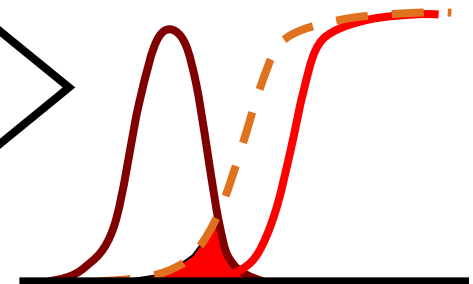
Material

$[csm/0/90/csm/\pm 45/csm]_s$

v_f=52%

E-glass/Vinyl Ester

•Owens Corning Fabric

•Dow Derakane – 640-900

•Pultruded @ Dow Freeport, TX

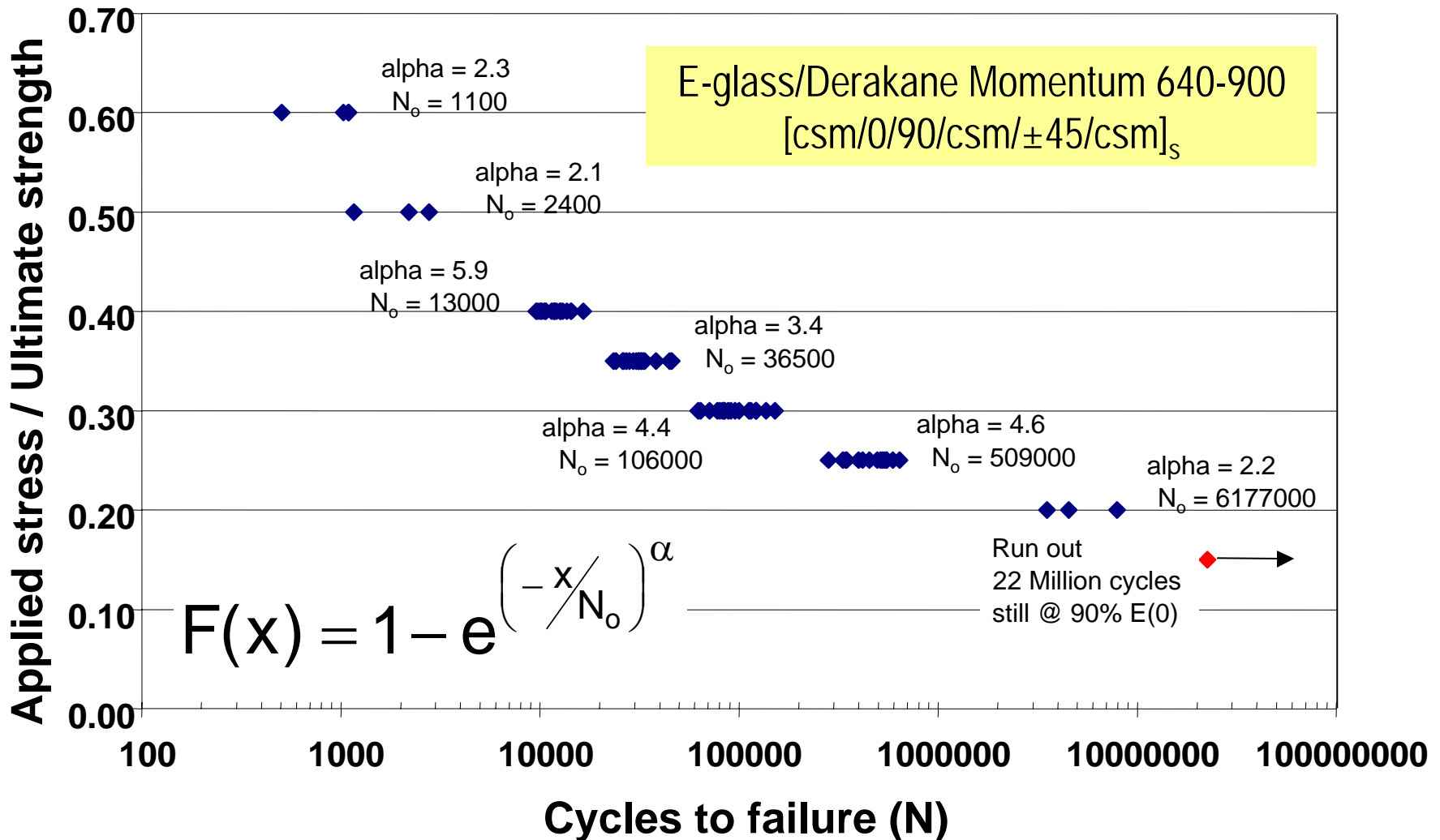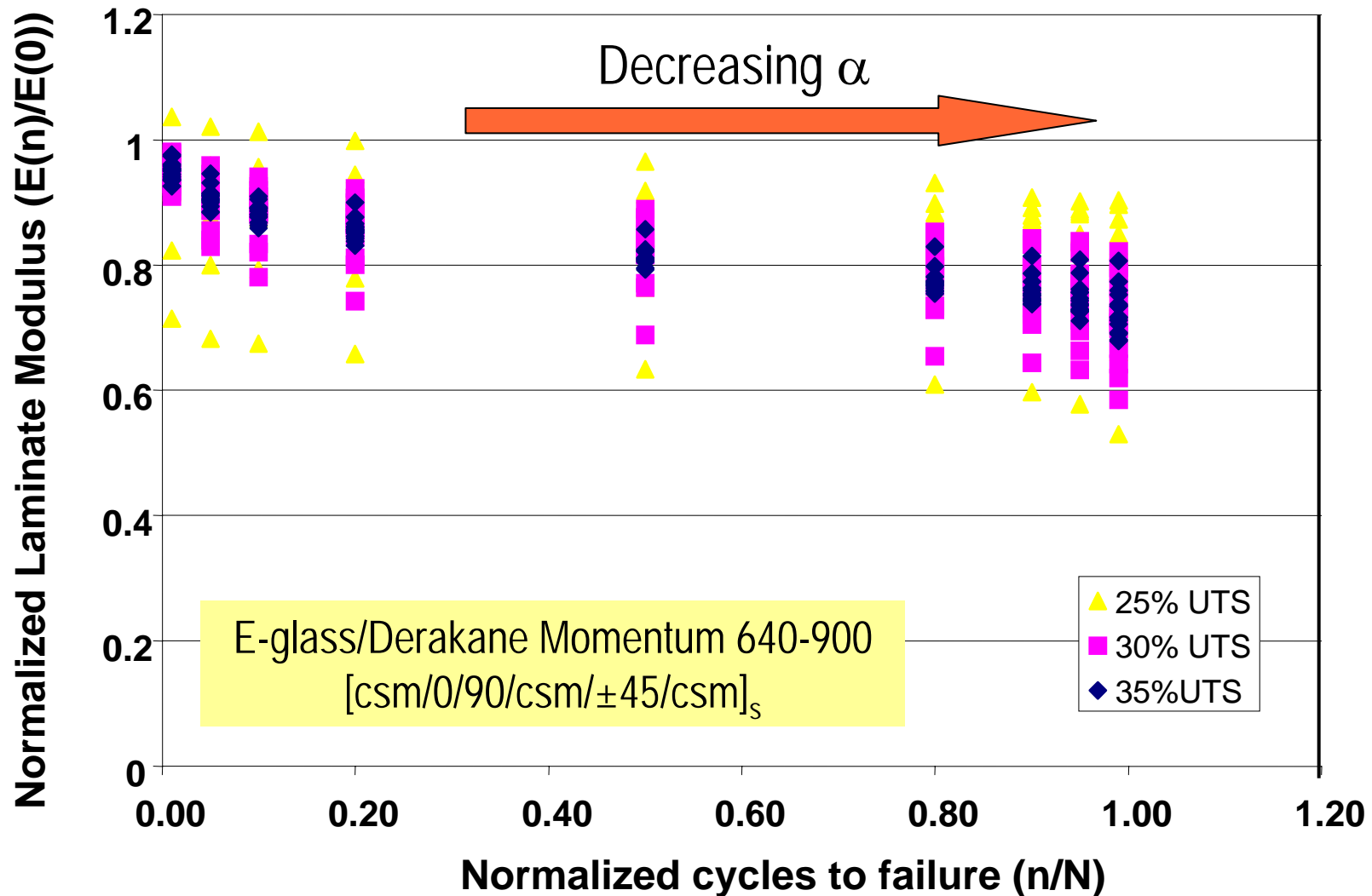| |
|---|
| Nexus 110-039, 0.18mm |
| xCDM 1810 =⁻ xx mm @ 55vol% in the C and D layers and @ 28vol% in the M layer |
| xDBM 1710 = yy mm @ 55vol% in the C and D layers and @ 28vol% in the M layer |
| CSM M8643 CSM, Mat 1.0 oz = 0.48 mm @ 28 Vol% glass |
| xDBM 1710 |
| xCDM 1810 |
| Nexus 110-039 |

Material Variation: Fatigue

E-glass/Derakane Momentum 640-900
$[csm/0/90/csm/\pm45/csm]_S$

$$F(x) = 1 - e^{\left(-x/N_o\right)^\alpha}$$

alpha = 2.3
$N_o = 1100$

alpha = 2.1
$N_o = 2400$

alpha = 5.9
$N_o = 13000$

alpha = 3.4
$N_o = 36500$

alpha = 4.4
$N_o = 106000$

alpha = 4.6
$N_o = 509000$

alpha = 2.2
$N_o = 6177000$

Run out
22 Million cycles
still @ 90% E(0)

Applied stress / Ultimate strength

Cycles to failure (N)

Laminate Modulus Reduction

Stiffness Reduction: α Variations

E-glass/Derakane Momentum 640-900
[csm/0/90/csm/±45/csm]$_s$
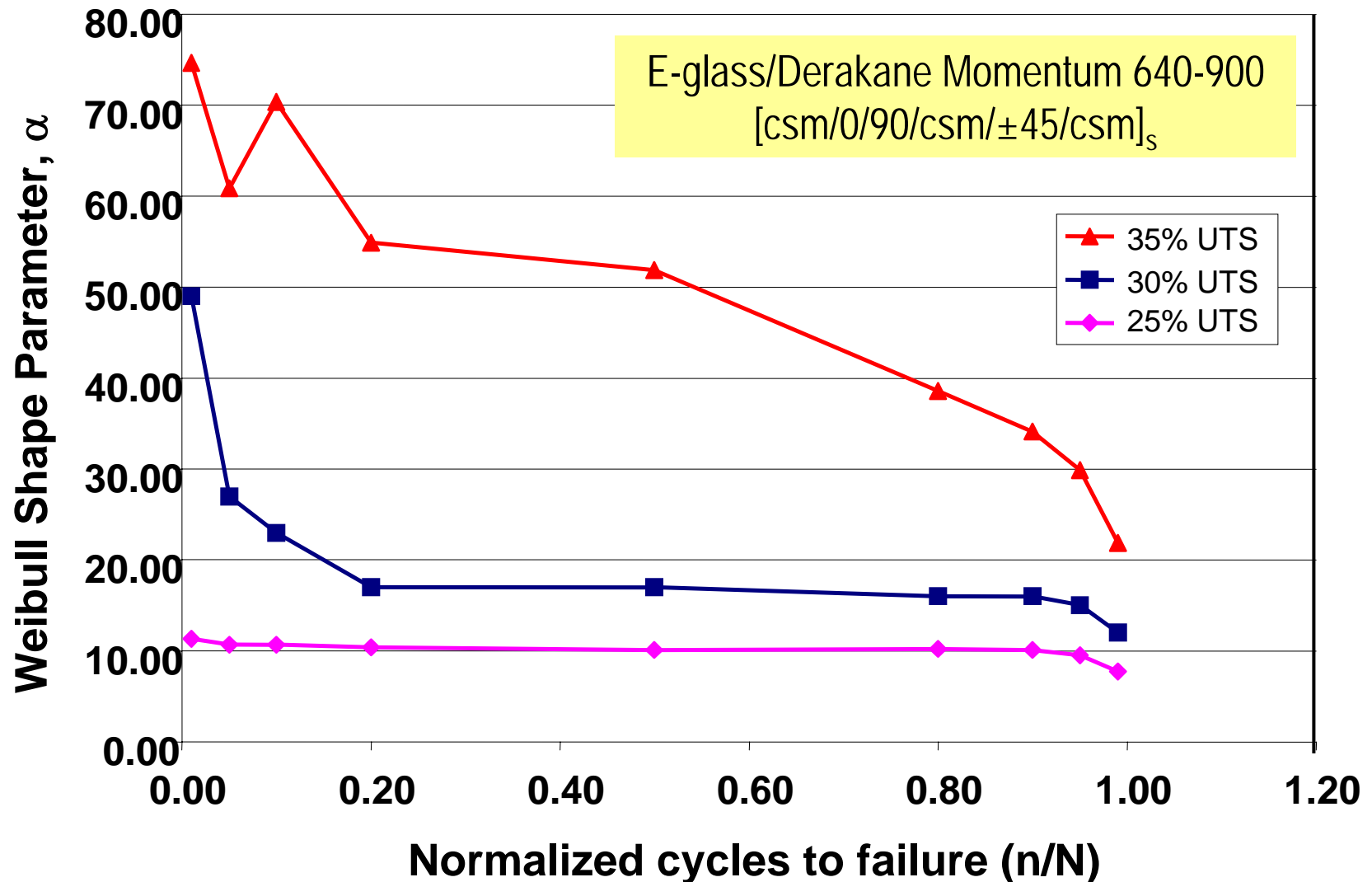
Remaining Strength & LRFD Preliminary Trials

Create Loading history

↓

Random Initial Material Properties (Monte Carlo)

↓

CLT

↓

$$Fr(n) = Fr(0) - \int\limits_{0}^{\frac{n}{N}} (1 - Fa(n)) \cdot J \cdot (\frac{n}{N})^{J-1} \cdot d(\frac{n}{N})$$

↓

Material Evolution

For N cycles

↓

LRFD

For i trials

Fatigue Validation

Applied stress / Ultimate strength vs Cycles to failure (N)

E-glass/Derakane Momentum 640-900
$[csm/0/90/csm/\pm45/csm]_S$

- alpha = 2.3, N_o = 1100
- alpha = 2.1, N_o = 2400
- alpha = 5.9, N_o = 13000
- alpha = 3.4, N_o = 36500
- alpha = 4.4, N_o = 106000
- alpha = 4.6, N_o = 509000
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Fatigue at 35% UTS for 18750 cycles or $(\mu-2*\sigma)$

Run out
22 Million cycles
still @ 90% E(0)
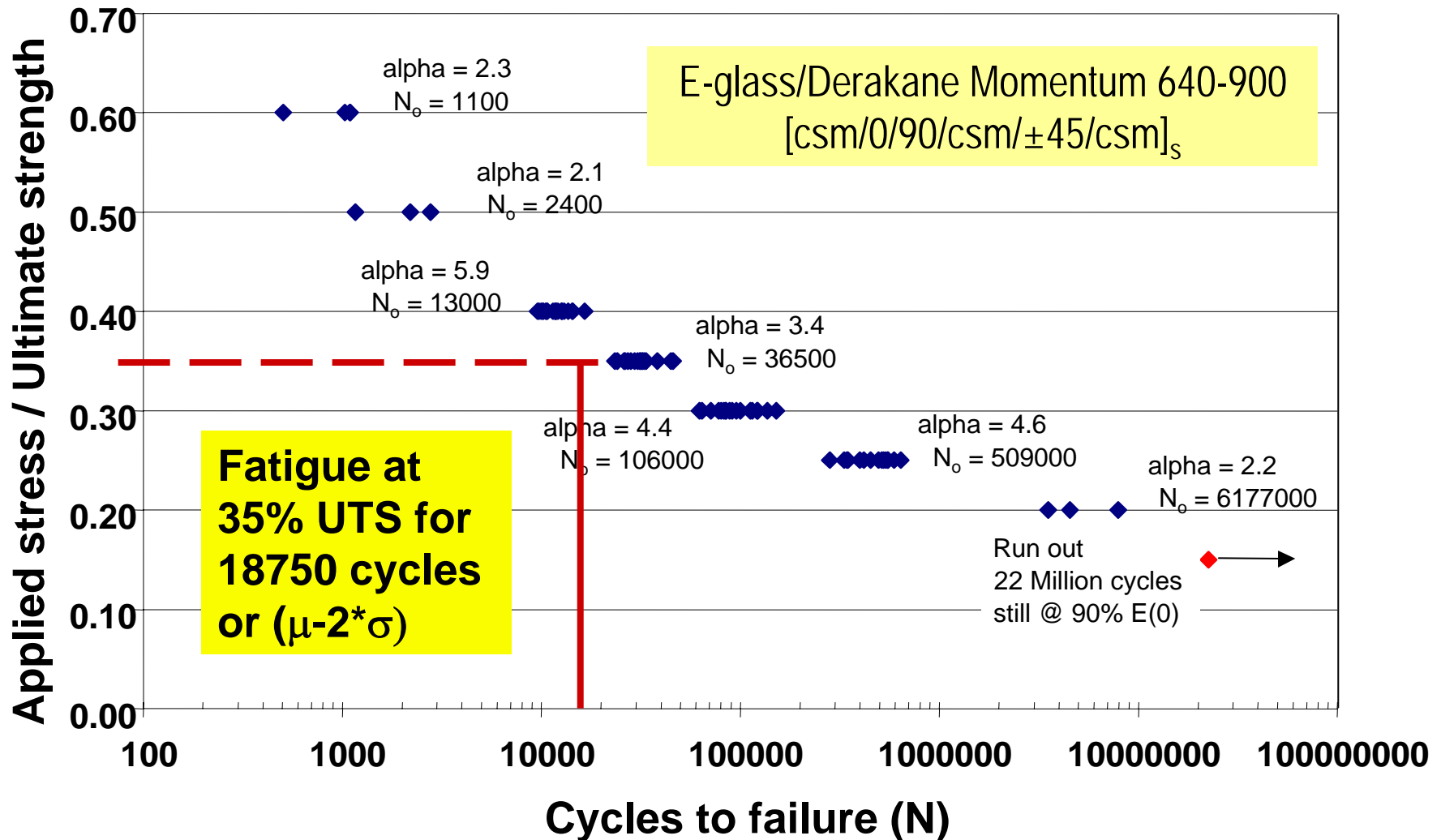
Simulated Case: Fatigue
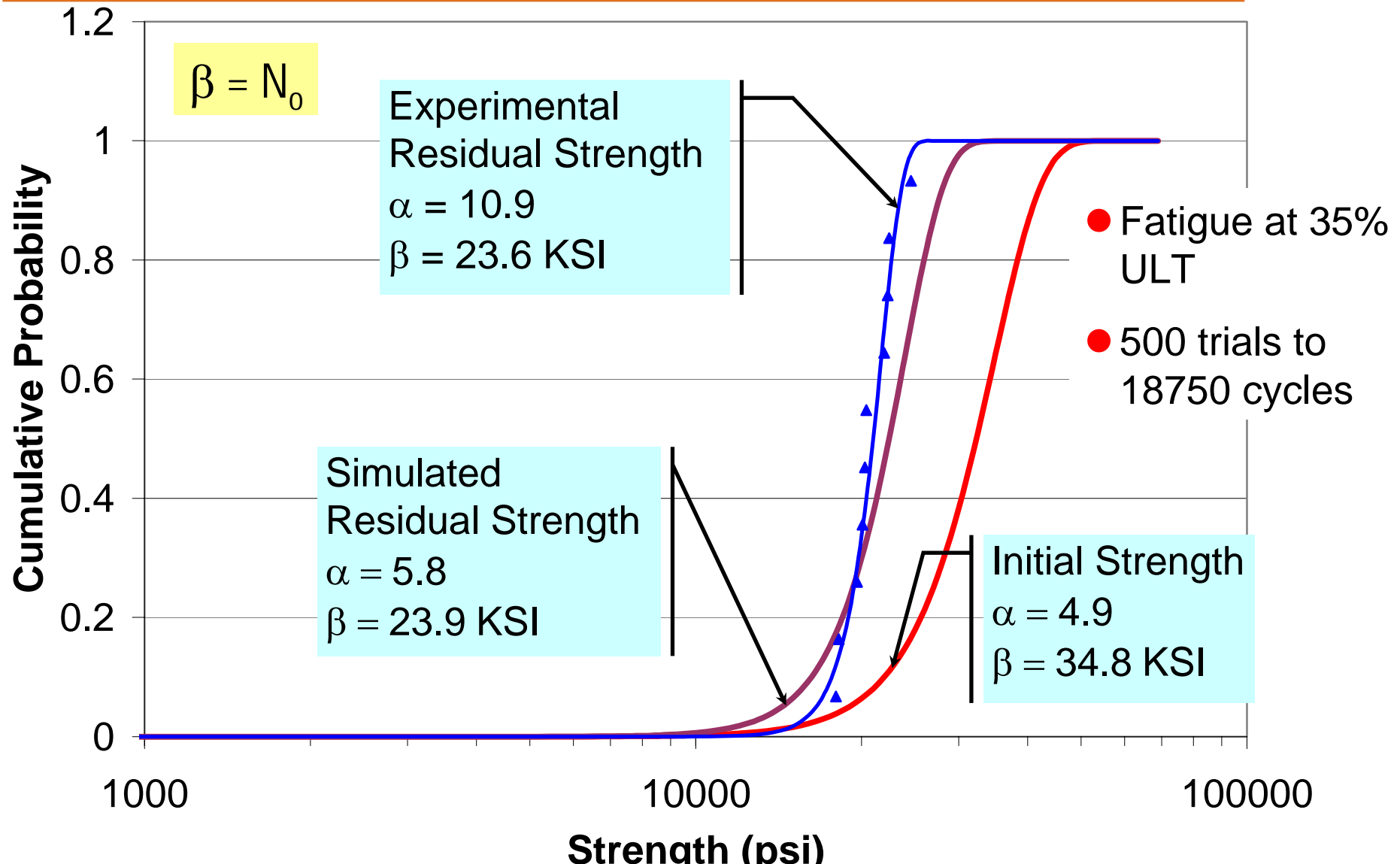
Validation: Coupon Level

- **_Experimental:_ 15 Samples fatigued at 35% ULT to 18750 cycles or to failure – Survivors' residual strength measured**

- **_Simulation:_ 500 trials to 18750 cycles or (μ-2*σ)**

$\beta = N_0$

Residual Strength Distribution		
Weibull Parameter	Experimental	Simulated
α	10.9	5.8
β (psi)	23.6 E 3	23.9 E 3

Probability of failure during fatigue before the sample reached 18750 cycles	
Experimental	Simulated
23%	23%

MRG Qualifications

- Members to the International Editorial Boards of the ASCE *Journal of Composite for Construction* & the *International Journal of Fatigue*

- NSF CAREER Award 1997

- Textbook: *Damage Tolerance and Durability of Material Systems*

- *MRLife:* Licensed code for the assessment of composite durability

- Sponsored Research: $8 million in Corporate, State and Federal grants (over 7 years)

- *Design Manual Development* for composite structures
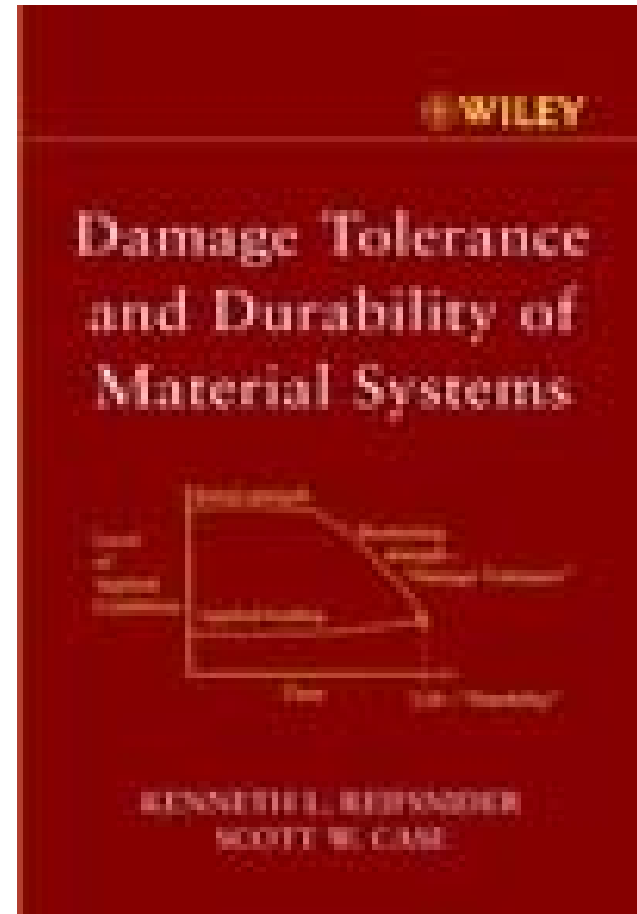
MRG Facilities

- Experimental characterization & validation including combined hygrothermal-mechanical-loading facilities

- Analysis & modeling at multiple length and time scales

- Visualization & immersive environments